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ABSTRACT

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An interdisciplinary approach was taken to investigate ~~the~~ structure-property relationships in fibrous composites subjected to various stress states and environmental conditions. The ultimate goal ~~of these efforts~~ was to reinforce our ability ~~in optimizing~~ the fracture resistance in composites. The concept of controlled interlaminar bonding (CIB) was proposed and evaluated as a possible approach of improving the impact energy-absorbing capability or the damage tolerance in composites. Thickness-direction fibers, as introduced by stitching or braiding, can improve the interlaminar shear strength and interlaminar fracture toughness, thereby reducing or suppressing delamination in advanced composites. Failure mechanisms in the composites subjected to impact loading were investigated. The most critical material parameters that dictate the impact penetration resistance of composites were identified. ~~The~~ failure mechanisms of hybrid composites were studied as a function of fiber properties and stacking sequence. A new sensor for ballistic impact studies was developed. The effect of residual thermal stresses on the impact response of composites was measured. New techniques for ~~the determination of~~ residual stresses and internal damages in composites were discussed. A new energy-based fracture criterion for composites was proposed. Equations for determining the strain energy densities in composites under various loading modes were derived. A new way of determining the stress intensity factor in composite was developed, an ~~Finally,~~ applications of the J-integral approach to composites fracture problems were discussed.

(determining)

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OPTIMIZATION OF FRACTURE RESISTANCE IN COMPOSITES

A Final Report

written by

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1. FOREWORD

The present research was aimed at improving the basic understanding of the structure-property relationships in fibrous composites subjected to various stress states and environmental conditions. The ultimate goal of these efforts was to reinforce our ability in optimizing the fracture resistance in composites. Several approaches to achieving this goal have been taken. These include:

(1) Manipulation of the interlaminar phase:
The concept of controlled interlaminar bonding (CIB) was proposed and evaluated. On the one hand, perforated plastic films were inserted in laminates to promote energy-absorbing delamination during impact loading, while otherwise maintaining adequate static strength during normal service life. On the other hand, selected tough and compatible polymer films were incorporated in the interlaminar zones (interleaving) to toughen brittle fiber composites by reducing delamination and improving damage tolerance.

(2) Development of multidimensional fiber preforms:
Thickness-direction fibers, introduced by stitching or braiding, can improve the interlaminar shear strength and interlaminar fracture toughness, thereby reducing or suppressing delamination in advanced composites.

(3) Measurement of residual thermal stresses:
The effect of residual thermal stresses on the impact response of composites was evaluated. New techniques for the determination of residual stresses in composites were discussed.

(4) NDE assessment of damage:
New NDE techniques for the assessment of damage in composites were developed and evaluated.

(5) Advancement of composite fracture mechanics theories:
A new energy-based fracture criterion for composites was proposed. Equations for determining the strain energy densities in composites under various loading modes were derived. A new way of determining the stress intensity factor in composite was developed. Applications of J-integral approach to composites fracture problems were discussed.

(6) Understanding of composite response to impact loading:
Failure mechanisms in the composites subjected to impact loading were investigated. The most critical material parameters that dictate the impact penetration resistance of composites were identified. A new sensor for ballistic impact studies was developed.

(7) Fiber selection and hybridization.
Interlaminate hybridization was evaluated as a possible way of improving the impact response of composites. The failure mechanisms of hybrid composites were studied as a function of fiber properties and stacking sequence.

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3. THE REPORT

A. STATEMENT OF THE PROBLEMS STUDIED

Fracture resistance of fiber reinforced polymer composites is a very complex subject for research. The fracture behavior of a composite is not a unique function of the constituent fibers and matrix; the fracture properties cannot be predicted by a simple rule-of-mixture law. The fiber-matrix interactions, the fiber orientations or stacking sequence, and the processing conditions are all important factors to be considered. The stressing conditions and the environments to which the composites are subjected also play a key role in determining the failure processes of composites.

The fracture resistance of composites subjected to impact loading, with both low and high incident energies, is the primary subject of the present report. Fiber composites are known to be highly susceptible to internal damage caused by a low-velocity impact. The composites can be damaged beneath the surface with relatively light impact, while the surface remains undamaged to visual inspection. As a result, their local strengths are significantly impaired and their durability in the service life reduced. Research efforts on the low-velocity impact are usually aimed at reducing the degree of damage (in the form of transverse cracking and delamination) to improve the post-impact integrity or damage tolerance of composites. On the higher incident energy side, a greater energy-absorbing capability for improved impact penetration resistance is the primary goal of research.

The impact response of composites has become a critical subject of composites research [1-25]. However, our grasp of the impact response in composites is still quite limited, possibly because this complex phenomenon involves many different interactions and parameters [26-31]. Studies of impact damage in composites can be divided into three areas: impact dynamics and damage mechanics [4,8,15-21,35], post-impact residual property characterization [6,7,9-12], and damage resistance improvements [5,14,39,53]. The present study emphasized the third aspect although part of the efforts was devoted to addressing the first two areas.

Various approaches have been used to improve the damage tolerance (low-velocity or low-energy impact) or penetration resistance (high-energy impact) of composite materials. These include control of fiber-matrix interfacial adhesion [36,55,56], matrix modifications (in particular, rubber toughening) [14,23,53], lamination design (e.g.,selection of laminate stacking sequence) [41,57], introduction of through-the-thickness reinforcements (X-D composites produced by braiding, 3-D weaving, and stitching) [58,59], insertion of interlaminar "interleaf" layers [60], fiber hybridization [40,42-44], and utilization of high-strain fibers [34,38-40].

The last approach appears to be very promising since a major cause of impact related problems in high performance composites is believed to be related to their low strain to failure. In general, it is the low ductility fibers, rather than the relatively high-strain matrices, that limit the composite strain. A study was therefore undertaken to understand why certain fibers possessing both high ductility and high strength might impart a great impact and penetration resistance to fiber composites. Prevailing deformation and fracture mechanisms in these materials under various loading conditions were studied, with the major material parameters dictating such mechanisms identified. The effects of fiber hybridization on the mechanical behavior of composites were also investigated. The techniques of stitching were selected to introduce the thickness-direction fibers in the hope that delamination can be reduced or suppressed in laminates. The mechanical properties of these 3-D composites were examined.

The concept of "controlled interlaminar bonding (CIB)" was explored with two seemingly conflicting ideas evaluated. On the one hand, perforated brittle polymer films (e.g. polyimide) were inserted inbetween fiber-epoxy prepreg layers to improve the toughness without significantly sacrificing the strength of composites. These CIB layers were added to promote delamination and to divert/blunt brittle cracks in composite. These layers are particularly useful when a high energy-absorbing capability (e.g. for ballistic impact protection) is required. On the other hand, relatively tough "interleaved" layers (e.g. thermoplastic or toughened thermoset adhesive films) can be inserted in composites to absorb energy from low-velocity impact and to provide some interlaminar ductility; these help to reduce delamination and improve damage tolerance of composites.

To put our research efforts concerning composites failure on a more unified basis, various failure criteria for composites were reviewed and a new criterion was proposed. New fracture mechanics approaches were developed. Effective NDE techniques for residual stress measurements and damage assessment in composites were also investigated. As a by-product of the present research, a new micro-velocity sensor was invented for the determination of energy loss mechanisms in fabric and composite materials subjected to ballistic impact.

B. SUMMARY OF THE MOST IMPORTANT RESULTS

(1) THE RESPONSE OF FIBROUS COMPOSITES TO IMPACT LOADING

The Effects of Fiber Properties

The response of advanced composites to low-velocity projectile loading was investigated. The impact failure mechanisms of composites containing various fibers with different strength and ductility were studied by a combination of static indentation test, instrumented falling dart impact test, and scanning electron microscopy (SEM). The composites containing fibers with both high strength and high ductility (eg., PE fibers) demonstrate a superior impact resistance as compared to those containing fibers with high strength (eg., graphite) or high ductility (eg., nylon fibers) but not both.

Upon impact loading, the composites containing PE fibers usually exhibited a great degree of plastic deformation and some level of delamination. These permitted a greater volume of material to deform and crack, thereby dissipating a significant amount of strain energy, before the penetration phase proceeded. When the incident energy was less than 100 joules and the sample-clamping ring greater than 2 inches, no through penetration was observed in all the samples containing more than three layers of PE fabric except when loaded at relatively high rates and low temperatures. Although certain levels of delamination also took place in other composite systems, very little plastic deformation occurred, allowing ready penetration of the projectile. The penetration resistance of composites appeared to be dictated by the fiber toughness; a high modulus or a high ductility alone is not sufficient to impart good penetration resistance to composites. A high fiber toughness is required and this property must be measured in a simulated high-rate condition.

Impact response of Composite Sandwich Panels

The impact response of various composite sandwich panels was investigated in relation to the constituent material properties. This investigation leads to the following conclusions:

1. The impact energy absorbed by a composite sandwich panel containing single-layer facesheets increases many fold compared to that of the foam core when alone. Such a sandwich combination offers exceptional impact resistance and yet maintains its light-weight characteristics.

2. The impact response of composite sandwich panels is mainly controlled by the facesheets and is practically insensitive to the density of the PVC foam core, provided the facesheet material is sufficiently tough (e.g., containing PET or high-strength PE fibers).

3. The impact failure mechanisms of the composite sandwich panels made of less tough facesheet material such as graphite fibers tend to be foam-core-dominated, provided the PVC foam core possesses a relatively high density.

4. The maximum load and the total absorbed energy of the single-layer composite facesheets declines as the impact velocity increases.

5. The energy absorbed by the composite sandwich panels containing the low-density PVC foam core is about 15% to 100% greater than the sum of the energies separately absorbed by the two facesheets and the foam core. This percentage deviation from the rule-of-mixtures prediction increases as the density of the foam core increases. However, this deviation will be insignificant if tougher facesheets, such as PE fibers, are used.

Fracture Behavior of Stitched Multidirectional Composites

An experimental approach, primarily based on high strain rate impact and low strain rate flexural test methods, has been employed to evaluate the mechanical properties of the stitched 3D composites and their 2D counterparts. Failure mechanisms in these materials were also determined using in situ optical microscopy and SEM. The test results and the post-failure fractography of this study lead to the following conclusions.

(1) Multidimensional (3D) composites have been found to possess greater damage resistance than conventional 2D composite materials. Loading rate

plays an important role in determining the impact resistance of a composite laminate. The 3D composites, regardless of the matrix types (whether they be epoxy or PP) demonstrated an excellent impact resistance when subjected to a low velocity flexural impact.

(2) The stitched third-direction Kevlar fibers have proved to be effective in arresting delamination propagation. A 3D composite has a smaller damage area (with little or no visible delamination) than that in a 2D composite. As observed in both flexural load-displacement curves (three-point and four-point bending) and the plots of load vs. time as well as energy vs. time (instrumented impact), the failure process in 3D composite usually proceeds gradually (retaining structural integrity for a longer period of time) while a 2D composite usually fails in a sudden catastrophic manner. This observation is also confirmed by microscopy.

(3) The technique of stitching through prepreg layers often results in a localized in-plane fiber damage. The stitched 3D composites, although having improved damage resistance, often exhibit a lower flexural strength when compared with 2D composites. Composites fabricated from stitched fabrics are much less prone to such fiber damage than those from prepreg materials. The 3D graphite-epoxy composites have been found to have a poorer flexural strength than their 2D counterparts. Kevlar-epoxy and Kevlar-PP composites appear to be more immune from such a fiber damage.

(4) The failure mechanisms in both 2D and 3D composites are strongly dependent on the composite types and the loading directions. In general, a 2D composite loaded in the Z direction tends to have matrix-dominated fracture. Interlaminar delamination was usually found to be the dominant failure mode in 2D composites. For a 3D composite tested in the same direction a fiber-dominated mode usually predominates. In this case, major fracture features were fiber buckling, fiber breakage, interfacial debonding and fiber pull-outs. When loaded in the Y direction, both 2D and 3D composites fractured in the fiber-dominated mode. The 3D composites usually experienced a smaller distortion (smashed) zone but a higher degree of fiber breakage and fiber pull-outs.

(5) Thermoplastic composites in general have greater damage tolerance than thermoset composites. The fibers damaged in a stitched fiber preform therefore have less effect on the mechanical properties of a thermoplastic composite than it does on a thermoset composite.

(6) Stitching has been found to be a way to introduce third-direction fibers in an otherwise 2D composite. However, hand stitching inherently involves misalignment of third-direction fibers. Stitching through prepreg layers tends to generate damage in the prepreg material. Other techniques are being sought for producing multidirectional preforms.

<u>Impact Response of Hybrid Composites</u>

The energy absorbing mechanisms of hybrid laminates in response to impact loading were investigated. The following conclusions have been reached:

1. Polyethylene, PET, and nylon fibers, when combined with epoxy resin,

have been shown to absorb large amounts of energy prior to failure of composites. These fibers can be used in hybrids to improve the impact resistance of various composite materials. A large impact toughness of constituent fibers is essential to achieving improved impact resistance in hybrid laminates.

2. The impact energies of the interlaminated hybrids generally showed a negative hybrid effects, i.e. slightly lower than what would be predicted by the rule-of-mixture law. However, the maximum loads often showed a positive synergism.

3. The technique of interlaminate hybridization was found to increase the tendency to delaminate in response to impact loading. Delamination was an effective energy absorbing mechanism in hybrids.

4. The impact load-vs.-time traces further confirm the speculation that indentation of the front surface represents the very first stage of loading, which controls the initial laminate stiffness during impact. Perforation induced by indentation was found to be the commanding failure mechanism in the brittle laminates studied. The laminates containing tougher fibers were capable of responding to impact in flexure without perforation. This process of plastic deformation to form a dome helped to disperse a major portion of the strain energy.

5. Many different macroscopic failure mechanisms in hybrid laminates can occur during impact loading. Laminates with an alternating stacking sequence usually exhibited a combination of through penetration and delamination, the latter being in the dagger shape and visible from both sides. For unsymmetric hybrid laminates containing two or three layers of PE or PET fabric, the impact energy depends on which side facing the impact direction but, in general, is higher than its alternating-sequence counterpart. In most cases, failure in these materials involved perforation, delamination and some tearing of the more brittle layers in conjunction with deflection of the tougher layers, provided that the tougher side faced the impact direction. When the more rigid side was struck first, these stiff layers were perforated with a lesser degree of plastic deformation occurred. With some exceptions, this process was followed by through penetration of the tougher layers, leading to an inferior energy absorbing capability.

6. The ductility index was generally found to decrease with increasing energy absorbing capability of a laminate, implying that, for tougher composites, mare energy will be dissipated to reach the maximum load than afterwards. This observation again suggests the significance of fiber properties in controlling the strength and, therefore, the impact resistance of composites.

<u>The Effects of Temperature and Moisture</u>

An extensive impact loading program was undertaken to study the fracture mechanisms in fiber-epoxy composites as a function of temperature and environment. It was found that, in general, the lower the test temperature the higher the impact energy. The specimens tested at a lower temperature are characterized by a greater level of micro-cracking and delamination. These phenomena are believed to be promoted by the higher residual thermal stresses. Slight exposure of composites to moisture or liquid nitrogen environment did not affect the impact response.

A simple thermo-mechanical analysis was presented to estimate the residual thermal stresses on cooling from cure or crystallization temperature to an end-use temperature (23 and -196 C). Experimental efforts to measure the mechanical bond between a fiber and matrix appear to yield results consistent with the prediction that the fabrication stresses would be higher with a larger temperature differential between the processing and the end-use temperature.

(2) A NEW SENSOR FOR BALLISTIC IMPACT STUDIES

An air gun based on helium propulsion was designed, constructed and tested at Auburn University's Materials Engineering. A high pressure helium storage tank (up to 6000 psi) was used to supply the helium gas required for propulsion. A high pressure regulator and a high pressure Asco valve were used to transfer the high pressure helium gas from the storage tank to two small cylinders (total volume of the cylinders is about 1000 cc). A pressure gauge was used to ensure the proper pressure in the intermediate tanks. When the proper conditions have been attained, a fast acting valve (from fully closed to fully open condition in 50 milliseconds) was activated and the pressure burst accelerated the projectile through the barrel to hyper-velocities. The gun itself consisted of two separate components. A liner (36" long) constituted the main barrel component. This liner consisted of two halves for easy of machining (no boring was necessary). A long semicircular 1/8" radius groove (36" long, the length of the liner) was machined on each half of the liner. When assembled this liner became a long barrel with a 1/4" diameter hole through the center. This liner was clamped tightly between two clamping plates using closely spaced bolts to ensure even distribution in pressure.

Prior to firing, the projectile was inserted from the open end using a long rod. During the flight of the projectile, it was accelerated to the desired velocity through the barrel and then passed through the **microvelocity** sensor unit (to be described below), impacted on the target and then exited into the catcher at the end.

The projectiles used in the preliminary study were all 1.75" in length and 1/4" in diameter. Different length and different materials can be used if required. A small magnet was inserted into the end of each projectile. The purpose of this magnet will be discussed in the next section. The magnets were cylindrical in shape and each measured 1/8" in diameter and 1/8" in length.

Muzzle velocities were measured as a function of helium gas pressure used. The velocities were measured using the **microvelocity** sensor. We are now in the process of increasing the velocity by modifying the intermediate storage system to ensure rapid flow of gas during propulsion.

An innovative microvelocity sensor unit capable of measuring the instantaneous velocity before, during, and after projectile-material interaction has been developed at Auburn University. The prefix "micro" refers to the superior spatial resolution of this device. In this system, a magnet was attached to the projectile rod. A detector made of a series of coils on an electrically insulating tube was placed in front of the materials of interest. (We are now experimenting with non-insulating tube). During the impact and the penetration of the projectile through the protective material, the magnet in the projectile triggers the coils in succession as a result of the rapidly changing magnetic flux the individual coils experienced. The proper timing of the triggering will therefore provide the needed information on the real time, real space velocity mapping. All the similar sensor units available in the market can only measure velocities averaged over a distance of at least one foot. This is far poorer than the spatial resolution required for ballistic studies where the entire slowing down process occurs over a 1 inch distance. To determine the dynamic energy loss process, spatial resolution in the order of 0.1" is required. To overcome the signal overlap problem at less than 0.1" separations, a special digital electronic circuitry was developed and tested at Auburn. In this design, there are separate raw signals in the form of a sine function from individual detector coils (here, only five such signals are shown. In real situation, there will be 11 to 21 coils). The problem here is that the signals are not separable when simply added together due to overlapping. A digital circuitry was designed, constructed and tested. Each raw signal was fed individually into separate comparator circuit and the output signal became digitized square wave. However, these digitized 5V signals were still too wide to be useful. They were then fed into individual lead edge detectors. The output of these signals had adjustable widths from 50 ns upward. These narrow signals were then summed together and provided detail information on the instantaneous positions of the projectile as a function of time. The final signals were displayed and stored on a Tektronics digital storage oscilloscope. The pulses represent the passing of the magnet in the projectile through the eleven coils. In the case of a free-flying projectile through air, the constant distance between pulses signifies constant velocity without slowing down.

A secondary coil unit was designed and constructed to measure the exit velocity of the projectile. This unit consisted of two coils spaced 2.5" apart and was placed behind the target. Due to the large distance between the coils (2.5"), the two raw signals are completely resolvable and therefore need not be processed. To further improve the spatial resolution of the sensor, a new coil is now being wound which has 0.05" inter-coil spacings. This new detector will have 21 coils over an overall length of 1 inch.

(3) THE CONCEPT OF CONTROLLED INTERLAMINAR BONDING (CIB)

Controlled Delamination (To enhance the energy-absorbing capability during a high-energy impact)

The concept of controlled interlaminar bonding (CIB) has been proposed as a means of improving the composite toughness without degrading the strength.

Failure mechanisms in several different types of composite laminates were investigated. This study leads to the following conclusions:

(1) Incorporation of an appropriate amount of perforated interlayers can increase the fracture toughness of composite laminates without significantly decreasing the material strength.

(2) These interlayers appear to promote delamination that would aid in dissipating strain energy as well as diverting and blunting a propagating crack through the Cook/Gordon mechanism.

(3) The amount of delamination depends upon the competition between the Griffith crack and the delaminating crack. The competition seems to be a function of the relative magnitudes of interlaminar strength and composite cohesive strength. The former is determined by the degree of perforation and lamina surface treatment.

(4) Failure mechanisms of composite laminates are found to be different when the loading directions of samples are varied in a three-point bending test or a Charpy impact test. The degree of delamination and the total absorbed energy are also varied correspondingly.

(5) The technical feasibility of the CIB concept has been demonstrated. However, optimal conditions for balanced composites properties have yet to be identified.

<u>Interleaving</u> (To improve the damage tolerance of composites)

Efforts were made to evaluate the effectiveness of interleaving in toughening brittle fiber composites. Thin layers of epoxy resins modified with either liquid reactive rubber (CTBN) or polyurethane were incorporated in the interlaminar zones in carbon fiber reinforced epoxy composites. The fracture behavior of such interleaved composites was studied. The following is a summary of the more important results of this investigation.

1. The G_{IC} values of composites can be increased by 25% to 50% by the technique of interleaving. However, since some fiber bridging phenomenon was observed on the fracture surfaces, the obtained G_{IC} value was fiber-dominated and did not represent the fracture resistance of the interlaminar resin. The degree of improvement should likely have been better if the effect had not been overshadowed by the fiber bridging phenomenon.

2. In general, the G_{IIC} values of the interleaved composites are 2 to 3 times greater than that of the control samples. The interleaf resin appears to be capable of undergoing extensive plastic deformation, as is evidenced by the larger and more extensive hackles observed on the fracture surfaces of interleaved composites. This high energy-dissipating capability under the complex stress fields at the interlaminar zone is believed to be one of the primary origins of the improved fracture toughness of interleaved composites.

3. In response to the impact penetration tests, the interleaved laminates absorbed 2 to 3 times more impact energy than the control samples due to the

high fracture toughness of their interleaf layers.

4. The damage tolerance of interleaved composites, as assessed by the impact fatigue test, is much greater than that of the control sample. This implies that one of the important beneficial effects of interleaving is the improvement in delamination resistance.

5. The fracture toughness, as measured by a compact tension test, of a moderately ductile resin (WPE 185-192) toughened with CTBN rubber particles is more than 3 times greater than that of the untoughened resin. However, the toughness of the resin with a high crosslink density (WPE 110) was not improved by much by the addition of CTBN rubber particles.

6. A good correlation between the G_{IIC} values of interleaved laminates and the G_{IC} (fracture toughness) values of their corresponding interleaf resins was observed. The higher the fracture toughness of interleaf resins, the higher the interlaminar cracking resistance of interleaved laminates.

7. SEM observations indicate that except the laminate interleaved with pure CTBN, the type of crack propagation under mode II condition tends to be "adhesive failure" in nature. To Increase the fracture toughness of interleaf resins without improving their bonding strength with the host prepreg resin will be of limited value in toughening the composites, since the interleaved composites would then fail by interlaminar separation between the interleaf and the host resin without fully using the fracture toughness of interleaf layers.

(4) NEW NDE TECHNIQUES FOR FLAW DETECTION AND DAMAGE ASSESSMENT

Flaw Detection and Damage Assessment

A digital comparative holography technique has been developed which is useful for detecting flaws in composites and evaluating their severity. The method consists of creating two double exposure holographic fringe patterns indicating the displacement fields of flawed and unflawed components. Using digital image processing and numerical algorithms, the interference fringes are then "compared" to determine the net additional specimen displacement due to the presence of the flaw. Also, a hybrid stress analysis computer model has been formulated and programmed to calculate the additional stress and strain fields due to the presence of the flaw. In this procedure, the experimental subtracted displacement data are used as input boundary and constraint conditions on a numerical plate solution using the finite element method.

Determination of Residual Stresses In Composites

Analytical, experimental, and numerical approaches of engineering mechanics have been pursued for evaluation of residual stress fields in composites. The analytical approach has consisted of the formulation and development of specialized computer programs which are able to implement lamination theory predictions of the residual stress and strain distributions produced in unconstrained laminates due to temperature changes such as those experienced during curing processes. The software incorporates a large yet conveniently utilized material database to insure flexibility.

In the experimental aspect of this research, embedded electrical resistance and fiber optic strain gages are being investigated. The use of optical fiber gages represents a new contribution. This portion of the research is still in progress.

In the numerical aspect of this research, the finite element method has been utilized on the both micro and macro scales to examine the stresses in fiber- matrix systems due the curing process and mismatched coefficients of thermal expansion. On the micro scale, the residual stress distributions produced in a section of a single-ply unidirectional laminate are being calculated. The analysis is fully three-dimensional and considers finite sized fibers within a polymeric matrix material. On the macro scale, the stresses, strains, and deformations in thin composite plates are being calculated using both the Ritz method and the finite element method. In both solution procedures, modeled loadings include transverse/in-plane concentrated forces and applied pressures, and constant or linear temperature changes through the plate's thickness. In the finite element procedure, a new three node triangular Kirchhoff plate element is used which is an improvement over the Zienkiewicz plate element widely used for isotropic materials.

(5) NEW FRACTURE MECHANICS APPROACHES FOR COMPOSITES

A New Energy-Based Failure Criterion for Composites

A widely used fracture mechanics concept, the strain energy density factor or "S-criterion" originally proposed by Dr. G. C. Sih of Lehigh University, was re-evaluated. The results of our numerical, experimental, and theoretical analysis indicate that this S-criterion can be successfully applied to explain the cracking behavior in a homogeneous and isotropic solid. However, when used in orthotropic materials, this theory, as originally presented, does not appear to be adequate. A new hypothesis is being developed for the prediction of crack initiation conditions and crack propagation direction. Well supported by the data of numerical calculations, this hypothesis suggests that, for composites subjected to Mode I loading, crack initiation is dictated by the dilatational strain energy density factor. For Mode II loading, however, the distortional energy density factor is the controlling parameter. Analytical equations have been derived to express stress fields as well as total, dilatational, and distortional strain energy density factors for a composite loaded at an arbitrary angle with respect to the unidirectional fiber direction. These equations will prove useful for future composite fracture analysis.

New Methods for Stress Intensity Factor Determination In Composites

Methods have been developed for accurate calculation of stress intensity factors in composite materials using stress and/or strain and/or displacement data obtained away from the crack tip. Although such methods have been employed in the recent past for linear elastic isotropic media, no former work has been done in the area of orthotropic composite materials. The new techniques are based on the retention of higher order terms in the stress/strain fields of a cracked specimen which satisfy the given boundary conditions. A form of the collocation method is then used to transform data away from the crack into a value for the stress intensity factor. Initially, the finite element method was used to generate the necessary input data to the theory at points away from the crack tip. Recent work involves the use of experimental data obtained with photoelastic coatings and strain gages

C. LIST OF ALL PUBLICATIONS AND TECHNICAL REPORTS

REFEREED JOURNAL/BOOK PUBLICATIONS

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2. W. K. Shih and B. Z. Jang, "Instrumented Impact Testing of Composite Sandwich Plates", J. of Reinforced Plastics and Composites, 8 (1989) pp. 271-298.

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12. J. Panus, B. Z. Jang, and C. Z. Wang, "Impact and Fracture Resistance of Hybrid Composites", submitted to Polymer Composites, 12/89.

13. B. Z. Jang, M. Cholakara, W. K. Shih, "Mechanical Properties in Multidimensional Composites", Submitted to Polymer Composites, 10/89 (Invited contribution)

14. R. H. Zee, B. Z. Jang, A. Mount and C. J. Wang, "Microvelocity Sensor For Instantaneous Velocity Determination", Review of Scientific Instrumentation, 1990, in press. (galley proof returned to publisher)

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2. B. Z. Jang, M. Cholakara, J. H. Kuo,"Mechanical Properties of 3-D Composites" SPE ANTEC, 1989, NYC.

3. B. P. Jang, C. Christienson, L. R. Hwang, and B. Z. Jang,"Impact Fatigue Testing: A New Methodology for Damage Tolerance Assessment of Fiber Composites", 34th SAMPE International Symposium, 5/89.

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5. W. C. Chung, B. Z. Jang, L. R. Hwang, T. C. Chang, "Damage Tolerance of Multidirectional Fiber Reinforced Composites", 33rd SAMPE International Symposium, Anaheim, Ca. March, 1988.

6. B. Z. Jang, L. C. Chen, R. H. Zee, W. K. Shih, Y. H. Hwang, "Instrumented Impact Testing of Composite Laminates: Data Analysis and Interpretation", International Symp. on Testing and Failure Analysis of Materials (ISTFA'88), Los Angeles, Ca. 10/88.

7. B. Z. Jang, L. C. Chen, W. K. Shih, and R. H. Zee, "Impact Failure Mechanisms In Hybrid Composites", ISTFA'88, Los Angeles, Ca. 10/88.

8. B. Z. Jang, M. Cholakara, L. R. Hwang, and T. C. Chang,"Deformation and Fracture Behavior of 3-D Composites", SAMPE International Symp., Las Vegas, 5/89.

9. T. S. Chen, M. Cholakara, T. L. Lin, and B. Z. Jang,"Mechanical Properties of X-D Composites Containing Mixed Fibers" International Conf. on Composite Materials (ICCM-7), Aug. 1989.

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19. Pearce, L. J. and Suhling, J. C., "Investigation on the Thermally Induced Mechanical Behavior of Laminated Composite Plates," to Appear in the Proceedings of the 1990 SEM Spring Conference on Experimental Mechanics, Albuquerque, NM, June 3-6, 1990.

THESIS, DISSERTATION, UNDERGRADUATE SENIOR PROJECT REPORTS

Cheng-Hsiung Lin (M.S. 8/1989)
[Thesis Title: "A New Digital Comparative Holography Technique for Detection of Flaws in Composite Materials"]

Larry J. Pearce (M.S. Expected 3/1990)
[Thesis Topic: Evaluation of Residual Thermal Stresses in Composite Laminates Using Finite Element Methods]

Gary G. Genge (M.S. Expected 3/1990)
[Thesis Topic: Development of Numerical Algorithms for Optical Nondestructive Evaluation of Composite Laminates]

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